20 Challenges for the Next Decade of Research on Below-ground Interactions in Tropical Agroecosystems: Client-driven Solutions at Landscape Scale

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(General Editors)

Key questions

1. So what? After we have answered all the questions previously asked in this book, how can farmers and agroecosystems benefit?
2. How can different types of knowledge and understanding be integrated to allow an evaluation of 'complex agroecosystems'?
3. Which research topics emerge as particularly relevant to this subject?

20.1 Introduction

Over the past five decades, great progress has been made in terms of agricultural productivity, both globally and in a number of tropical regions – although per capita food production in sub-Saharan Africa did decline. This increase in the production of main staple food crops is generally referred to as the 'Green Revolution'. In the early stages of the Green Revolution, research was directed mainly at plant breeding, fertilizer use and plant protection. However, the pace at which advances are being made is slowing, and there is increased awareness of the 'downside' associated with the loss of crop diversity.

The annual increase in cereal yields in developing countries has fallen to just under 1%, compared with 2.9% from 1967 to 1982. As a consequence, more attention has recently been directed at increasing the productivity of land and water resources (Kijne *et al.*, 2003). Further incentive for the agricultural research and development community to take this direction has come from considerations of sustainability.

When applied to the use of land and water, 'sustainability' means meeting the production needs of present land users whilst conserving, for future generations, the resources on which production depends. Such an approach is known as 'integrated natural resource management' (INRM), and

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requires a major shift in both research and management approaches. It differs from the Green Revolution approach in several ways. First, it often focuses on the needs of the poor farmers, integrating the interests of community-level land users and managers as well as national and international policy makers. Secondly, it focuses on environments with a high diversity, in which Green Revolution solutions are not readily acceptable or applicable. Thirdly, it focuses on the functions of natural capital in agriculture, in order to increase productivity whilst ensuring the sustainability and stability of any increases.

The majority of this book (Chapters 1–17) was devoted to helping the reader gain a better understanding of below-ground interactions at the plot level. The last part of the book (Chapters 18 and 19) made steps towards a landscape-level understanding of natural resource management issues (Fig. 20.1).

In this chapter, using examples from Africa, Asia and Latin America, we will illustrate how a better understanding of below-ground interactions is vital if some of the major INRM problems are to be solved. In each example, we begin by stating the problems that should be addressed by research, followed by the approaches currently being taken and the major challenges for the future. We hope that this will help the reader 'put the pieces of the puzzle together' and see how a better understanding of below-ground interactions can help in solving real-world problems and rural livelihood issues.

20.2 Example 1. Lake Victoria Basin

Lake Victoria, surrounded by Kenya, Uganda and Tanzania, is the world's second largest freshwater lake, having a surface area of approximately 68,000 km^2 and an adjoining

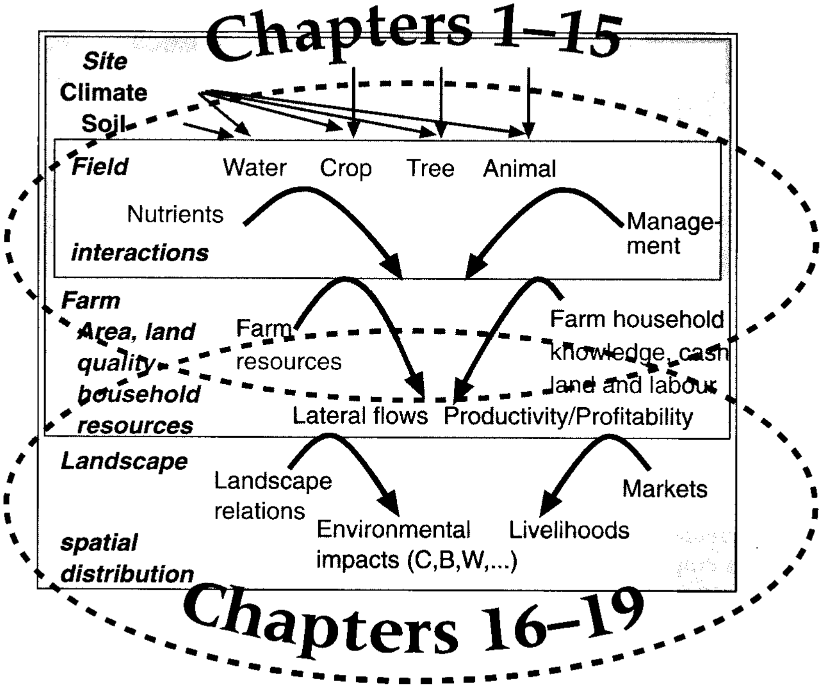

Fig. 20.1. Nesting of relations between local conditions (such as site, climate and soil), the field-level interactions between water, crops, trees and animals, farm-level use of resources and their impact on lateral flows, productivity and profitability and the landscape-level issues of environmental impacts (C, carbon stocks; B, biodiversity; W, watershed functions) and livelihoods.

catchment area of 155,000 km^2, and comprising 12 major river basins. Lake Victoria is a world-renowned site of vertebrate diversity, containing an estimated 500 species of fish (mostly endemic members of the family Cichlidae). It is ranked second in the world in terms of fish species richness, and is probably the site of the world's fastest proliferation of vertebrate diversity (because hundreds of fish species evolved in less than 12,400 years). However, it is also well known as the site of the world's largest contemporary species extinction event, linked to the introduction of one of the largest freshwater fish (Nile perch, *Lates niloticus*). This fish now supports the world's largest freshwater fishery, in Lake Victoria.

The Lake Victoria basin supports an estimated 40 million people, who produce an annual gross economic product in the order of US$3–4 billion (Sida, 1999). With the exception of the city of Kampala (Uganda), the lake catchment economy is principally agricultural, involving a number of cash crops, fisheries and types of subsistence agriculture. The quality of the physical environment is crucial if the living standards of the growing population are to be maintained or increased. It is estimated that a 5% reduction in the productivity of the region would lead to a loss of US$150 million annually. The lake basin is a major source of food, energy, shelter, transport and drinking and irrigation water. It is also a repository for human, agricultural and industrial waste.

Recently, the environment of Lake Victoria has attracted the attention of policy makers, following its colonization by water hyacinth (*Eichhornia crassipes*), which blocked water transport and fishing activities. The communities living around the lake, who lived, predominantly, by fishing, were the most affected, because they could no longer go out to fish. For a few years, the problem was compounded by the fact that any fish that were caught were unfit for either export or local consumption (due to contamination with high levels of *Escherichia coli*, derived from human waste that had been disposed of in the lake). Colonization of the lake by the water hyacinth is largely attributed to: (i) increased levels of nutrients (particularly phosphorus and nitrogen) entering the lake from urban, agricultural and industrial sources; (ii) sediment deposits, originating from soil erosion due to poor upland management practices; and (iii) damage to the natural filter function of wetlands, especially around the mouths of rivers.

20.2.1 Root causes of the lake's ecological problems

The ecosystem around the Lake Victoria basin has undergone substantial changes during the last three decades as a result of two major human interventions in the basin. The first was the introduction of the Nile perch, which altered the structure of the food web. The second was an increase in nutrient flows into the lake from the surrounding catchments. The most urgent problems in Lake Victoria are the presence of water hyacinth, decreasing fish numbers, and poor water quality; however, the lake is not the *source* of these problems. The root cause of eutrophication (besides the disposal of sewage) is continuing land degradation, resulting from deforestation, settlement, farming and accelerated soil erosion. Sediment and nutrient loads in the lake are high and will further accelerate the process of eutrophication. Low levels of soil P are an agricultural problem in the area, and are partially linked to the excess of P in the lake. Urban runoff is also an important component in the pollution of the lake, and will worsen in the next few years. Industrial discharges and sewage will exacerbate this problem, especially as there are a large number of agroindustries in the Nyando River basin.

The Lake Victoria Environmental Management Program (LVEMP), a basin-wide project that has been funded by the World Bank and the European Union since 1995, recognizes the fundamental importance that wetlands play in the lake's ecology. The programme is responsible for implementing policy concerned with the sustainable development of such wetlands. This policy pays due regard to both their economic value and their ecological importance, including their value as a filter surrounding the lake.

Consultants working for LVEMP (Bullock *et al.*, 1995) have made recommendations that highlight the importance of monitoring the buffering capacity of the lake basin wetlands and integrating the socioeconomic concerns of people using the wetlands. However, wetlands continue to be drained for the purposes of agriculture, despite growing evidence that this practice is unsustainable and economically unsound (Ong and Orego, 2003).

Although it is widely agreed that nutrient levels in the lake have increased in recent decades, we do not have reliable information concerning the major nutrient sources and sinks. Nutrients enter the lake from different sources (i.e. agricultural, atmospheric, urban and industrial sources), but there is still debate as to the relative importance of each. Quantifying the relative contribution made by the various sources, as a first step towards abatement, is still a major challenge. Most methods are flawed or inadequate, because they are based on values extrapolated from either North America (Bullock *et al.*, 1995), small catchments in Tanzania (Scheren *et al.*, 2000) or from minor streams in Uganda, in which case the values were extrapolated from data covering only a single year (Lindenschmidt *et al.*, 1998). The three countries bordering Lake Victoria (Kenya, Tanzania and Uganda) have very different agroecosystems, topography and discharges into the lake. Such extrapolations are therefore grossly unreliable when applied to the whole basin, though the latter two studies might reflect differences in land use between the two countries. Nevertheless, these rough estimates indicate that the contribution made by agricultural lands accounts for about half the nutrient load entering the lake. Of the total amount of water entering the lake, 85% comes from rain falling directly on to the lake, whilst the remainder is carried to the lake by its 12 major rivers. There is an urgent need for more reliable data on the relative importance of each source, especially for the major rivers (such as the Kagera in the west). Recent analysis of these major river basins (made using satellite images) indicates that the Nyando and Kagera river basins stand out in terms of sediment transport capacity and average slope.

20.2.2 How will an understanding of belowground processes help?

Farmers in the Lake Victoria basin have realized that the decline in soil fertility that has occurred over the last five decades is a major concern for them. They have also realized that this decline is largely attributable to depletion caused by continuous cultivation, because only 10 kg of nutrients per hectare are applied annually (Smaling *et al.*, 1997).

Because P limitation is common in the area, crops, fallow species and trees with a high P use efficiency and specific P mobilizing properties are preferred (Chapter 7, *this* volume). Although agricultural plot or farm-level studies of erosion have consistently suggested the existence of high erosion rates in western Kenya, it is now commonly understood that much of the sediment is probably deposited elsewhere in the landscape, as opposed to directly into the lake (Chapter 18, this volume). Downward leaching and substantial accumulation of mobile nutrients, especially nitrate, have been well-documented in western Kenya (Chapter 6, this volume). Much progress has been made in terms of understanding and quantifying the processes involved in the retrieval of nitrate by perennials in agroecosystems (Chapters 6 and 10, this volume). Lateral movement of mobile nutrients has, however, not been considered in these studies. It was only recently that the magnitude of the erosion problem has been appreciated, through a combination of remote sensing, laboratory analysis of field samples (Shepherd and Walsh, 2002) and sediment coring. Sediment coring is currently being undertaken at the mouths of the Nyando, Sondu–Miriu and Yala rivers, in order to reconstruct the recent history of sedimentation in the lake. Preliminary analysis of the cores taken indicates that the sedimentation rate has been strongly influenced by El Niño events, which have a long-lasting effect. Dramatic increases in erosion were detected only in the last two decades: these coincided with the clearing of forests on a massive scale, for agriculture. Reflectance spectroscopy offers a potentially powerful 'pedo transfer' method with which to rapidly assess land degradation as well as soil fertility status (Shepherd and Walsh, 2002). The major challenge is to determine whether this approach can be used to detect changes in soil physical properties and pinpoint the 'erosion hotspots' associated with land degradation across the whole lake basin.

20.2.3 Challenges and opportunities for the management of the lake basin

Political leaders have recognized that there is a need to act to address the problems faced in the lake basin.

> The problems, challenges and opportunities posed by the Lake are today of such magnitude that they cannot be faced by the riparian states acting separately. Our challenge is to contribute to the development of a collective approach to roll back the environmental threat that hangs over the Lake and unlock the vast potential of the Lake for the benefit of the people in the region.
>
> (Minister of Foreign Affairs and International Cooperation, Tanzania, quoted in Sida, 1999)

Political recognition of the lake's problems and potential has resulted in the East African States making a concerted effort to set up a secretariat to coordinate and address cross-sectoral and transboundary issues (such as harmonizing laws and regulations, mapping pollution sources, and promoting sustainable development).

Information and knowledge are often the most limiting factors in watershed and basin management (El-Swaify, 2000). Information brokers (research organizations and universities) can assist in efforts to provide all stakeholders with a good information base, which will help them make decisions that affect their lives, their farm enterprises and their communities. Better information skills may also assist negotiations to manage or solve conflicts among stakeholders with competing interests (Chapters 18 and 19, this volume). Swallow *et al.* (2001) argue that research organizations can play key roles in the provision of both information and training, especially to governmental and non-governmental organizations.

A major challenge faced by policy makers is their limited understanding of the filter functions of vegetation in the landscape. For example, wetlands play a vital role in the lake basin, both as a major source of income for local communities and as a filter for sediments. However, they are traditionally undervalued by governments. Therefore, it is common for policy makers to declare state ownership of wetlands and riparian forests. Consequently, plans are still being formulated to convert critical wetlands to agricultural uses. Another challenge policy makers need to overcome is the misconception that there is a strong link between the ecological concept of lateral flows and deforestation. For example, the Mara river basin, which straddles Kenya and Tanzania, is critical to the survival of the pastoralists, farmers and fishermen in the area. The basin also controls the world's largest migration of wildlife, which takes place in the Mara–Serengeti ecosystem. The loss of a third of the forest at the river's headwaters in Kenya was believed to have decreased water flow by 40%. However, in actual fact, the reverse has been found to be true (Mungai, 2003).

In western Kenya, research has focused on the use of perennials to retrieve nitrate from depths and the need for the addition of phosphorus (Buresh *et al.*, 1997; Chapters 6 and 10, this volume). These technologies involving perennials (known as improved fallows) have proved to be tremendously successful in providing short-term benefits to small-scale farmers, as well as offering reasonable protection in terms of runoff and erosion control (Boye and Albrecht, 2002). On the steep slopes of southwestern Uganda, tree fallows have been developed that are more profitable and productive than traditional bush fallow or continuous maize (Siriri and Raussen, 2003). Although these simplified agroecosystems are not as stable and sustainable as the original multistrata rainforests, and although they are beginning to suffer from pests and diseases (Chapter 15, this volume), they provide some improved ecosystem and economic functions. They do, however, need to be further developed and integrated into farmers livelihood needs. An alternative is the development of multistrata agroforestry systems (such as those in Indonesia), which mimic the major ecological functions of the original rainforests (Chapter 1, this volume), but provide greater productivity and a high income (from fruits), in addition to carbon sequestration (Chapter 12, this volume) and sustainability benefits.

20.3 Example 2. Sumberjaya Benchmark for Watershed Function Conflicts

Sumberjaya (literally 'source of wealth') is a subdistrict in the mountain range (Bukit Barisan), which spans the island of Sumatra (Indonesia) and forms the upper watersheds of all major rivers on the island. Of the island's provinces, the southernmost (Lampung) has the highest population density (8 million people living on 3.5 million hectares), as well as the highest level of poverty. A considerable number of people in the lowlands depend on irrigation water and hydroelectric power provided by these upper watersheds. Thus, the relationship between the lower and upper watersheds is considered to be critical with regard to provincial natural resource management plans.

Although 32% of the province is officially considered to be 'state forest land', only 20% of this state forest land actually had intact forest cover in the mid 1990s; and, 'forest encroachment' has not stopped since then. At least half a million recent settlers live in state forest lands. The majority of people in Lampung province, for example, either consider themselves to be of Javanese or Sundanese descent, even though they were born in Lampung, or are recent Javanese or Sundanese immigrants. However, many settlers also come from neighbouring provinces in Sumatra. The ethnic diversity apparent among the 'Lampungese' is therefore considerable, reflecting multiple waves of immigration for which the rivers were the main conduit.

Economically, coffee production in the uplands is one of the major income earners in the province, with Sumberjaya district being one of the important production areas to have attracted large numbers of immigrants over the past few decades. Much of the land settled is, however, classified as 'protection forest', and thousands of families have been evicted and forcefully removed to 'transmigration' sites on the much poorer soils of the lowland peneplain, greatly increasing their poverty. During these evictions, villages were destroyed and the coffee plants of the pioneer farmers uprooted. During the 'Tanggamus' operation of 1990–1991, more than 3000 people were evicted from Purawiwitan, which was at that time a 'village' of 7000 people. During that campaign alone, more then 8500 people were evicted – almost 10% of the population of the Sumberjaya subdistrict at that time. In 1994, in a second campaign, more than 3000 people were evicted from the neighbouring village of Purajaya, and a further 1200 were evicted from Purawiwitan: almost 500 people were evicted from the smaller village of Muarajaya. Newspaper reports of the time reflect the violence associated with these evictions, including incidents in which people were burned inside their houses. These evictions were undertaken to safeguard 'watershed protection forest'. However, the areas designated 'protection forests' have not returned to natural forest, and the livelihoods of the settlers were seriously affected.

The Sumberjaya district coincides, approximately, with the catchment area of the Way Besai, one of the tributaries of the Tulang Bawang River (one of three major rivers in Lampung, the other two being the Way Sekampung and Way Seputih). The Way Besai is used as the water source for a hydroelectric power scheme, which involves a runoff dam. Electricity generation started in 2001, but was interrupted in 2002 by a landslide near the turbines. Though the landslide was actually the result of the construction of a poorly designed road, the slip has generally been blamed on 'deforestation'.

Recently, ICRAF initiated a project, in conjunction with national and international partners, to assess the relationship between land-use change and the efficiency of watershed functions. A key hypothesis for the Sumberjaya benchmark states that:

some farmer-developed agroforestry mosaics are as effective as the original forest cover in protecting watershed functions related to water yield and water quality, and hence a substantial share of current conflicts between state forest managers and local population can be resolved to mutual benefit.

20.3.1 How will an understanding of belowground processes help?

Current research (some of which is considered in Chapters 10, 18 and 19, this volume) has made clear that the evictions in Sumberjaya were based on an incomplete understanding of the consequences that coffee production systems would have for the watershed functions in that area (Fig. 20.2). On the other hand, transforming open, monocultural coffee systems into 'shade coffee' systems, where coffee is grown in conjunction with fruit, timber and service trees (e.g. *Gliricidia* and *Erythrina*) would provide a win–win situation, in which rural poverty could be reduced without risk to stream flow or (probably) water quality.

In an innovative form of 'negotiation support', a multi-institutional team is facilitating dialogue between local farm communities, local government (which is currently 'in charge' of natural resource management), forestry officials and representatives of the hydroelectric scheme. The initial outcome of these negotiations was the signing of a series of community forest management agreements in April 2002. These provide at least temporary security of tenure for coffee farms within 'protection forest' domain, provided that the groups concerned actively protect the remaining forest and maintain watershed functions (e.g. by introducing trees into the coffee gardens). Although

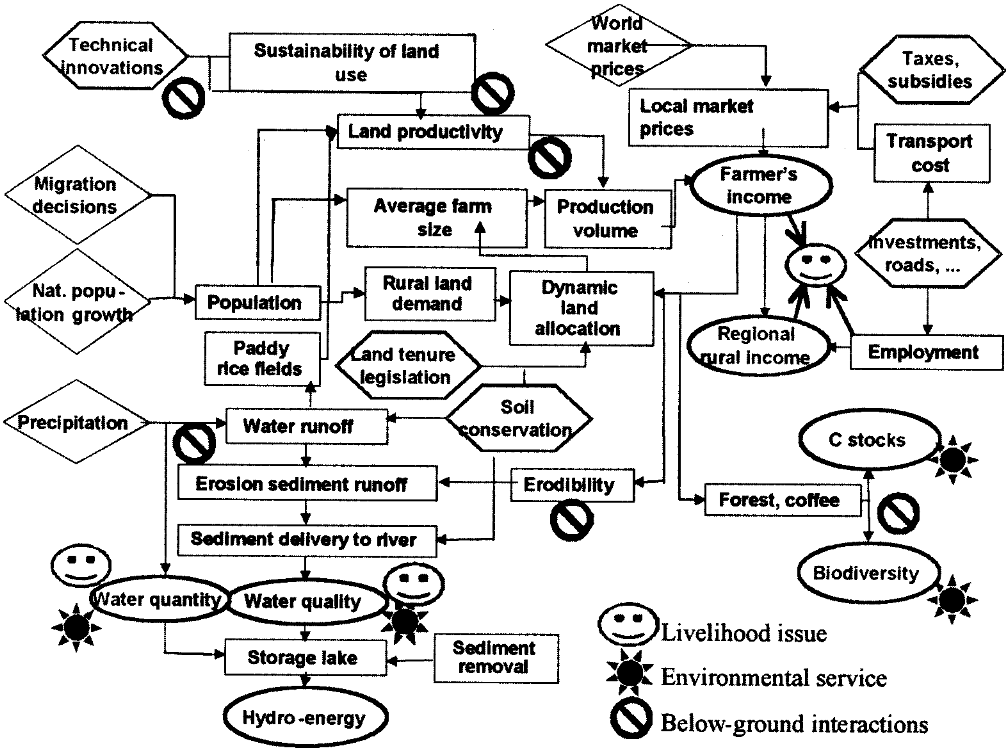

Fig. 20.2. Natural resource management system analysis of main relations in the Sumberjaya area, with special symbols for the key livelihood and environmental service outcomes, as well as the main places where 'belowground interactions' take place (nat., national).

these initial agreements are seen as 'policy experiments' (they have so far benefited only a few hundred families) other groups are anxious to follow the example being set. So far, however, no transparent mechanisms have been agreed upon that will allow either the monitoring of compliance with the agreements made or the evaluation of the environmental services provided. However, as part of the ongoing biophysical and ecological research in the area, progress is being made in testing candidate criteria that can be used to evaluate these environmental services. Furthermore, researchers have identified participatory methods of water quality monitoring, which have been used elsewhere in South-East Asia, as options that should be pursued. Clarifying these compliance and evaluation issues is important if we are to take this policy experiment beyond its current limits. For the farmers in the area, however, further economic benefits (beyond a reduced chance of being evicted) are important, especially as, globally, current coffee prices are low. Mechanisms by which farmers could benefit financially from the environmental services (i.e. the increase in terrestrial carbon stocks (van Noordwijk *et al.*, 2002) and maintenance of bird and other diversity) that their shade-coffee systems provide would be very welcome. Use of these mechanisms could further solidify the farmers' choice for environmentally friendly land-use practices.

Although the Sumberjaya subdistrict has experienced some of the most violent conflict, the conflicts over watershed function experienced by farmers in the upper watersheds have been repeated elsewhere, both in Indonesia and in other densely populated parts of Asia.

20.3.2 Challenges and opportunities for negotiation support informed by 'science'

The main opportunity Sumberjaya currently offers is that of learning from the process of negotiating land-use rights within the 'protection forest' domain. The primary rewards in such a situation are 'recognition' and 'loss of fear of eviction'. As the economic opportunities for productive land use are considerable, such rewards may be sufficient inducement at this stage for a switch to more environmentally friendly land-use practices. However, this still requires a degree of community coherence and collaborative action, which can be a challenge in areas where migrations have occurred recently. Research aimed at verifying and improving simple criteria could facilitate the process of switching to more environmentally friendly land-use practices, e.g. by blending our understanding of below-ground interactions, surface phenomena, agricultural productivity and landscape-level land-use planning. Such simple criteria could, in turn, be useful both in negotiations and in the subsequent monitoring of effects.

20.4 Example 3. Alternatives to Slash-and-burn in the Western Amazon Basin

The Amazon basin is the largest remaining area of intact tropical rainforest, although forest conversion is 'nibbling' at its outer edges and along all major new access routes. Much of the converted forest is used for pasture, which rapidly degrades in terms of productivity and which will only support low stocking rates per hectare and low human population densities. This contrasts with the 'slash-and-burn' conversion of forests in central Africa and South-East Asia, where the predominance of tree crops in land-use systems after forest conversion supports much higher population densities and where logging is a more important 'trigger' factor, creating and paying for access. Although the rate at which the Amazon is being 'colonized' is largely driven by macro-economic policies (increasing road access, subsidizing *colonistas*, and the pricing of main agricultural outputs), the wastefulness of converting forest into low-intensity land-use systems has stimulated efforts to develop more sustainable forms of land use in the form of 'improved pasture' or 'tree crops'. The widespread expectation that agricultural intensification can help relieve the pressure being placed on natural forests is based on an oversimplification. Agricultural intensification is certainly not in itself *sufficient* for the protection of old-growth forests (Tomich *et al.*, 1998; Angelsen and Kaimowitz, 2001; Lee and Barrett, 2001). Such intensification can, however, help in the context of specific forest protection, spatial land-use planning linked to the selective stimulation of road access, and a policy framework that balances economic growth and resource protection (Wunder, 2003).

20.4.1 Ecological problems associated with land-use intensification

The productivity of pastures derived from forest declines rapidly, unless specific efforts are made to introduce improved pasture grasses and adequate management practices (Toledo *et al.*, 1985). Nematode infestation (see Chapter 15, this volume), nutrient (N and P) deficiencies, overgrazing – which results in soil compaction and the predominance of a single species of (introduced) earthworm (*Pontoscolex corethrurus*) (Chapter 16, this volume) – can all be associated with pasture degradation. The recent use of spatial analysis in the state of Acre (Brazil) has indicated that, if planted with the main forage grass (*Brachiaria brizantha*), 72% of the area has soils that demonstrate a high risk of pasture degradation, whilst 9% demonstrate a medium risk and 20% a low risk (Valentim *et al.*, 2000). A better understanding of below-ground interactions is necessary for more sustainable pasture management.

An initial approach to the problem of pasture degradation is the development of mixed-species swards through the integration of pasture legumes. Such legume-based pastures have been shown to be more sustainable in relation to N cycling (Cadisch *et al.*, 1994b) and able to support a higher diversity of fauna (Decaëns *et al.*, 1994), but legume persistence is still a major challenge. One of the main agricultural alternatives to pasture development is the development of sustainable tree-crop production systems. Rather than the more intensive monoculture system of coffee production, agroforestry forms are receiving increasing attention. Of the 44,000 ha of agroforestry systems in the Amazonian state of Rondônia, 45% have coffee as one of their components. However, in this area, associations of trees and coffee (*Coffea canephora*) have only recently received research attention. Farmers quote the fluctuation of coffee prices, the forecast of persistently low prices in the coming years and the increase in production costs associated with using inputs (fertilizers, herbicides, fungicides, etc.) as the main reasons for the inclusion of trees among the coffee. Cordia wood (*Cordia alliodora*), bandarra (*Schizolobium amazonicum*), rubber (*Hevea brasiliensis*), pinho cuiabano (*Parkia multijuga*) and peach palm (*Bactris gasipaes*) are among the trees preferred.

20.4.2 How will an understanding of below-ground processes help?

The main limitations that farmers in this area mention as being those that affect the establishment of forest species in conjunction with coffee are: (i) a lack of information on the growth, planting density and the spacing of trees associated with coffee; (ii) a lack of seed; and (iii) the mishandling of seed (seeds of many species quickly lose their viability). A range of forest species exists among the 'forest coffee' systems. The decision to associate trees with coffee has been found, in this area, to depend more on socioeconomic factors than on biophysical ones, even though most of the producers interviewed (70%) were aware that the presence of trees benefits the environment. The choice of species used depends on the seeds and seedlings that happen to be available: farmers do not take into account the root type, crown form and size of the tree, even though their objective is, always, to produce wood for the market.

Many practical aspects of the interactions between trees and coffee remain obscure (Rodrigues *et al.*, 2002). Research is now beginning to consider the matter at a more fundamental level. For example, as part of a broader ecological comparison, researchers compared mycorrhizal spore diversity between coffee agroforestry and coffee monocultures in Rondônia (Brazil). This research found that, whereas spore numbers were lowest in coffee monoculture, spore diversity was lowest in the combination of pinho cuiabano (*Parkia multijuga*) and coffee (compare Chapter 14, this volume). Neither the expectation that complex systems will directly solve the problems associated with low nutrient availability and disease pressure, nor the thesis that they will only lead to competition, is particularly useful. Finding suitable combinations requires a careful search, especially in the case of migrant communities, which do not have access to traditional ecological knowledge of tree–tree interactions.

20.5 In Praise of Complexity?

20.5.1 Ecological versus agronomic functions

In the first chapter of this book, Ong *et al.* started, using a relatively simple method, to unravel the positive and negative aspects of plant–plant interactions, in so far as they determine the overall production of agroecosystems that have more than one component. Most of that analysis targeted tree + annual food crop systems; however, the basic concepts used are also valid for combinations of perennials, such as those found in multistrata coffee systems. Empirical separation of positive and negative effects has been found to be feasible, though the results are site-specific. Extrapolation of such 'interactions' to other conditions is difficult as, with relatively small shifts in overall growth-limiting factors, the interactions can change in character. The classical paradigm, of developing technology in pilot sites and then extrapolating ('scaling out') to similar places may be less feasible for more complex systems than it is for 'simple' agroecosystems.

Rather than trying all 2^n possible interactions in a system with n components (which is difficult even if n is only 3 or 4) we may benefit from using summary characteristics, such as system-level productivity and system-level environmental impact. Expanding on an analysis by Sitompul (2002), we can take the classical trade-off analysis between two components of an intercropping system and apply it to the 'relative ecological function' (REF) versus the 'relative agronomic function' (RAF) of agroecosystems. In schematic form, in the case of agroecosystems in dynamic landscapes that are undergoing intensification, a number of stages (A to E in Fig. 20.3) can be distinguished. During a trajectory such as that shown here, the trade-off between the REF and RAF alternates between being negative (lose–win), positive (lose–lose, win–win) and neutral (no change, win).

The following attributes of an agroecosystem can be included in the 'ecological function'.

- Local nutrient cycling and capture of nutrients before they leave the system via vertical or lateral flows of water or in a gaseous form (in which case they escape into the atmosphere). In Chapters 6 and 10, we saw that systems that include deeply rooted components with an undersaturated 'demand' for nutrients can indeed play a significant role in this regard.
- Full use of incoming water, as long as annual rainfall is less than evaporative demand. If nearly all incoming water is used by an agroecosystem in approximately the same way as the natural vegetation to which the landscape has adjusted, outgoing lateral flows of water will be small. This is important, because an increase in such flows can bring salt into circulation and have other negative effects downstream (Chapters 9 and 18, this volume).
- A level of organic inputs that allows the 'ecosystem engineers' among the soil fauna to play their role in the creation and restoration of soil structure, complementing plant roots that create channels in the soil and improve its structure by causing wetting/drying cycles (Chapters 11 and 16, this volume).
- Permanence of a litter layer on the surface of the soil, which protects the mineral soil layers from erosion through wind or water (Chapters 12, 18 and 19, this volume).

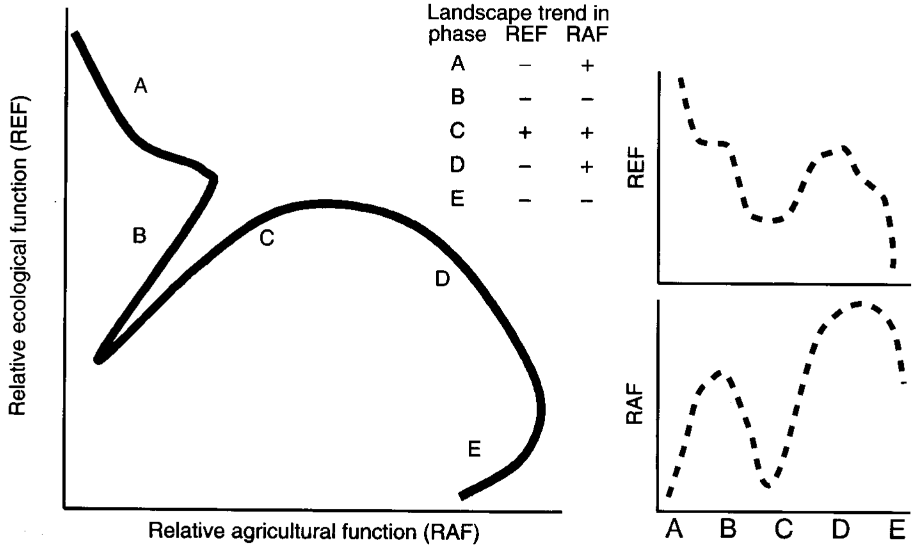

Fig. 20.3. Schematic relationships between REF (relative ecological function) and RAF (relative agronomic function) during a trajectory of 'agricultural intensification' (A–E); the diagram suggests that the overall trade-off is a negative one and usually the two move in opposite directions, but that phases where both REF and RAF decline (letters B, E) or increase (letter C) can defy this overall trend.

- A food web and ecological pyramid that: (i) is close to the potential dictated by energy flow in organic inputs to the below-ground system; and (ii) maintains internal controls that make pest population explosions (pest outbreaks) less likely (Chapters 15 and 16, this volume).

20.5.2 How much diversity is enough?

Although considering the broad trends of ecological and agronomic functions can both help us understand the big picture and help us identify those conditions in which a (temporary) 'win–win' situation is possible (such as phase C in Fig. 20.3), we may need to be more specific when considering the opportunities for beneficial interactions. Generally 'diversity' is associated with a 'cost' to agronomic functions, because of a quantity–quality trade-off that affects the use that farmers, as managers of agroecosystems, can make of their knowledge, and because of 'economies of scale' in mechanization, which favour more uniform crops and farm animals. So, how much diversity is enough?

Diversity of natural ecosystems tends to have a non-linear relationship with resource availability and levels of environmental 'stress' factors. The most diverse systems generally do not have the highest standing biomass or biological productivity (Fig. 20.4). Van Noordwijk and Ong (1999) tried to answer the question of how much diversity is actually needed to reduce the risk of production failure given the degree of variability that the environment imposes, which creates uncertainty for the farmer. As uncertainty increases the relevance of diversity, one can speculate that we will need more biodiversity in future, as global climate predictions for many tropical countries forecast more 'extreme' (less certain or predictable) weather conditions and hence increased stress and risk.

The results presented in this book show that below-ground diversity is, in fact, much greater than above-ground diversity. At the same time, however, there appear to be large 'redundancies', or at least aspects of diversity for which no functional value can be quantitatively assigned: we still know little about how much of this below-ground biodiversity

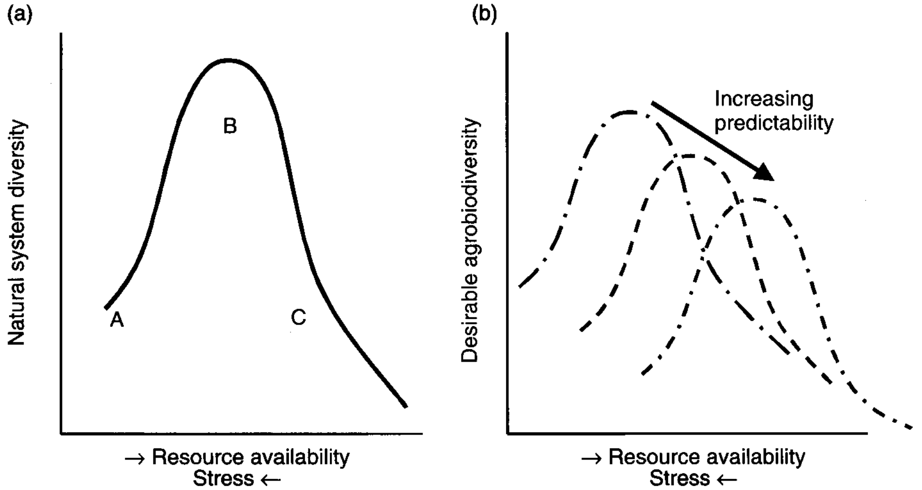

Fig. 20.4. (a) Schematic relationship between resource availability and levels of stress factors and the diversity of natural ecosystems (A, poor sites with only a few specialist species; B, intermediate sites with high diversity; C, rich sites with only a few dominant species). (b) Transfer of this concept to agroecosystems suggests that the optimum amount of diversity depends on the resource supply and stress factors, and on the predictability of the environment and the way products of agroecosystems are valued in human society.

we need for the system to be resilient. Some of the recent research presented here has shown that, despite drastic changes in land use, a large proportion of the organisms either remains present (in an active or dormant state), or is replaced by other organisms in the same 'functional' group.

We do, however, know that there exist a few essential specialists, which have a fundamental, unique impact (e.g. rhizobia, mycorrhizas, nitrifiers, and some pests, such as nematodes) and which today probably represent the most promising target group for interventions (e.g. improved management) by farmers. Examples of pest incidence still give the most compelling case for adopting a diverse system. Such a system need not necessarily be 'vertically' diverse (e.g. multistrata); the need could be fulfilled equally well by 'lateral' biodiversity (e.g. sequential systems) – the latter being easier for farmers to manage and mechanize. Even though 'vertical biodiversity' can lead to intense competition events that are often difficult to manage, or whose management is labour intensive, new approaches are emerging. In intercropping systems, there is a trend away from 1:1 species row schemes towards a system that reduces the interface between species by employing alternative options (such as 2 : 2, 4 : 2 or similar strip designs). These systems appear to be less risky and more profitable for farmers, and so merit further investigation. Mechanization of farm operations may also play a role in changing planting patterns (e.g. where bullock ploughing replaces manual tillage).

20.5.3 Knowledge

In the public debate on the 'desirability' of changes in agroecosystems, we may have to acknowledge important differences between the various interacting knowledge systems (Fig. 20.5). Such differences are related to whether a knowledge system is primarily based on categories and definitions or on observable phenomena and processes, plus inferences made regarding underlying processes and 'balance sheets'.

Farmer management of complex agroecosystems has to be based on monitoring, diagnosis, remediation, mitigation and adaptation, rather than on a blueprint predictability of the behaviour of the

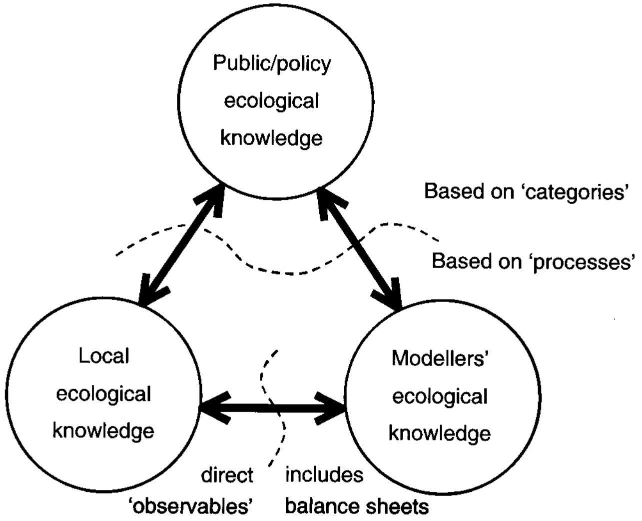

Fig. 20.5. Three types of ecological knowledge that interact in the public debate on the 'desirability' of changes in agroecosystems.

agroecosystem. The agricultural research approach, which involves clear-cut hypotheses and empirical tests of interventions in the form of technologies, has had a poor track record in this regard.

Increased and more quantitative understanding of below-ground interactions can help farmers improve their agroecosystems as long as it is:

- Able to provide explanatory knowledge, augmenting existing farmer knowledge of mechanisms.
- Articulated in ways farmers can relate to their own understanding of trade-offs between current productivity, lateral flows and long-term resource conservation.
- Phrased as generic principles that have a value that goes beyond a specific site.
- Embedded in diagnostic tools that can identify what we learn from and/or extrapolate to other places if we know a certain 'system' works at a given place.

As explored by Matthews *et al.* (Chapter 3, this volume) current simulation models still have some way to go before they will fully meet the above requirements. However, they have still become an essential part of the overall knowledge exchange. Models are not only a powerful tool with which to assess multiple interactions that would otherwise be too complex to evaluate but, crucially, they also allow us to quantify the importance (or unimportance) of potential interactions and improved resource uses. In future, this may help us better prioritize resources so that a significant impact can be achieved, rather than chasing scientifically interesting interactions that are of little consequence to the sustainability of the system or the livelihood of farmers. In this respect, recognition of who our clients are, and thus for whom such tools are being developed, is already pointing towards a more focused approach. But, we still lack the data necessary to better validate and calibrate our models.

For relatively simple systems, one can envisage simulation models that evaluate all feasible combinations of management interventions and search for the best 'package' of available options. In more complex systems, however, the number of feedback effects related to any farmer management decision is substantial, and we need to include the farmer's decision rules in the model. Models of such systems need to include equations that represent how farmers are likely to take decisions, based on information derived from the actual performance of the system and external variables. Simulations can then focus on the parameters of these decision rules rather than on a calendar listing of all the individual decisions. For example, rather than stating the desired frequency of pruning, a model user specifies at what size of tree and intensity of shading an intervention is desirable. This will then increase the actual pruning frequency if the growth rate of the tree increases. Pruning the tree has various effects on the other components of the system, via light intensity at ground (or crop) level, as well as the regrowth pattern of the tree, the 'leakiness' of the system in terms of water and nutrients (Chapter 10, this volume), the expected time till the next pruning intervention, and the use of labour, etc. Based on all such consequences, the model can evaluate the overall effect of the decision rules, and help to optimize management decisions.

20.6 Challenges for the future

The preceding chapters have yielded some conclusions that may have surprised the reader. Some of these deserve to be highlighted here.

- Legume-based systems are more 'leaky', in terms of leaching and greenhouse gas emissions, than low/no input conventional systems. However, when we consider that we need to intensify production in order to increase food supply, it is likely that legume-based systems will fare equally as well, or better, than traditional, fertilizer-based systems.
- Although we have in the past given a lot of attention to the use of spatial complementarity to capture resources (water, nutrients) located at depth, we have so far put little effort into understanding how these resources are recharged. This is a challenge, and points to the need to look at lateral flows and catchment events. Here we need to see erosion and leaching in a wider context (e.g. what is one farmer's loss may be a gain for the farmer further downstream).
- Management of water is critical (e.g. with respect to erosion, leaching, competition, P mobilization, rooting pattern and lateral flows). Given the predicted changes in global warming, water management will become even more important.
- What is or is not acceptable with regard to competition effects depends on the value of the components. However, the challenge associated with trees is that an originally attributed value (e.g. market value) may change during the lifetime of the tree and hence change the balance that governs what is viable and what enhances livelihoods of farmers. Thus, crucially, all components of a mixed-species system should have a considerable 'value' of their own. Then, not only does biodiversity provide a 'safety net' against risk, it also provides an economic buffer against human-induced changes.

In the preceding chapters, a large number of recommendations for further research have been made. Overall, we think that static concepts and tests (such as the 10–14 hypotheses formulated about agroforestry a decade ago, see Young, 1987) have played their role in stimulating research, and are no longer of much use. Instead, new experimental and modelling approaches are required, both at the level of system dynamics and at the level at which interactive management decisions are made by farmers.

Even though we have become increasingly aware of the potential that diverse systems have in terms of reducing external effects and increasing resource use efficiency, we still face the problem of actually measuring such events (particularly leaching and nutrient capture in 'filter' zones). To effectively manage a complex agroecosystem, a farmer needs ways to monitor or measure the real-time performance of the system. Currently, the way dynamic elements of below-ground growth and interactions are measured at the research level is very time and labour consuming. New methods need to be developed that will allow researchers to make real-time measurements with automated analytical software, allowing large datasets to be processed efficiently and immediately and so meaning those data would not take months or years to analyse. Examples include continuous non-destructive monitoring of root dynamics, soil solution nutrient concentrations, and water availability. New approaches are currently being developed, which allow, at least partially, more real-time observations such as these to be made (e.g. spectrometric approaches or non-destructive observations via tomography). However, all of these new 'gadgets' and tools may widen the gap between what a farmer understands and appreciates about a system and what a researcher can see. Therefore, efforts are needed to 'calibrate' such detailed methods against the simpler concepts that farmers use.

Ultimately, decades of research on managed tropical systems has given way to the recognition that the relevance of multispecies systems is largely determined by the preferences and priorities of farmers or communities. Thus a feasible beneficial species combination is not necessarily in itself sufficient argument for adoption. The various facets of a farmer's livelihood are thus crucial elements, and need to be considered when evaluating mixed-species systems.

But it is not only farmers who wish to capitalize on the benefits of mixed-species systems. In most societies, recognition is growing that natural and managed ecosystems have value beyond the farm products they provide. In this context, mixed-species systems may play an important role in providing biodiversity for recreational purposes, as well as being more efficient with regard to reducing negative externalities (e.g. pollution and greenhouse gases), which will help to provide a more stable world ecosystem. These increasingly and equally important considerations will drive research further away from the purely plot-oriented approach, towards approaches that consider the matter both at a landscape level and, finally, from a global perspective.

Conclusions

1. Multispecies agroecosystems, with their potential for synergy in terms of below-ground interactions, can offer improved farmer livelihoods and sustainability and basic ecosystem functions, at levels of complexity far below those of natural ecosystems.
2. Farmers increase or decrease the complexity of agroecosystems depending on their livelihood strategies. This has consequences for other stakeholders in the landscape, in terms of below-ground and above-ground lateral flows of water, nutrients, soil and organisms.
3. Understanding the root causes of land-use problems and the different ways they are perceived by different farmers, as well as by other local stakeholders, scientists and policy shapers, is essential for the development and introduction of sustainable solutions.

Future research needs

1. Identification of a wider portfolio of simple, manageable and profitable multispecies options, which exploit synergies in below-ground interactions, and which serve farmers' livelihoods and provide beneficial environmental service functions.
2. Development of methods that researchers can use to support farmers as managers of 'complex' agroecosystems. Rather than being based on 'packaged technology' options, such methods should be based on an understanding of basic principles, and should utilize tools for monitoring and evaluating the current status of the system.
3. Development of improved tools to monitor the impacts, at the landscape scale, of land-use decisions made at the plot scale.
4. Development of better ways to communicate results between different stakeholders.